

DIFFERENTIAL PRODUCTION CROSS SECTION WITH RESPECT TO JET MASS AND SUBSTRUCTURE IN CMS

**QCD @ LHC 2019
July 16th, 2019**



University at Buffalo

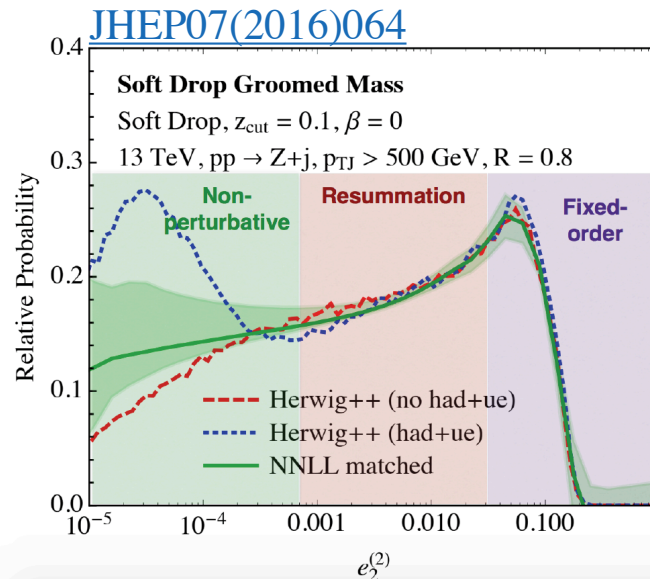
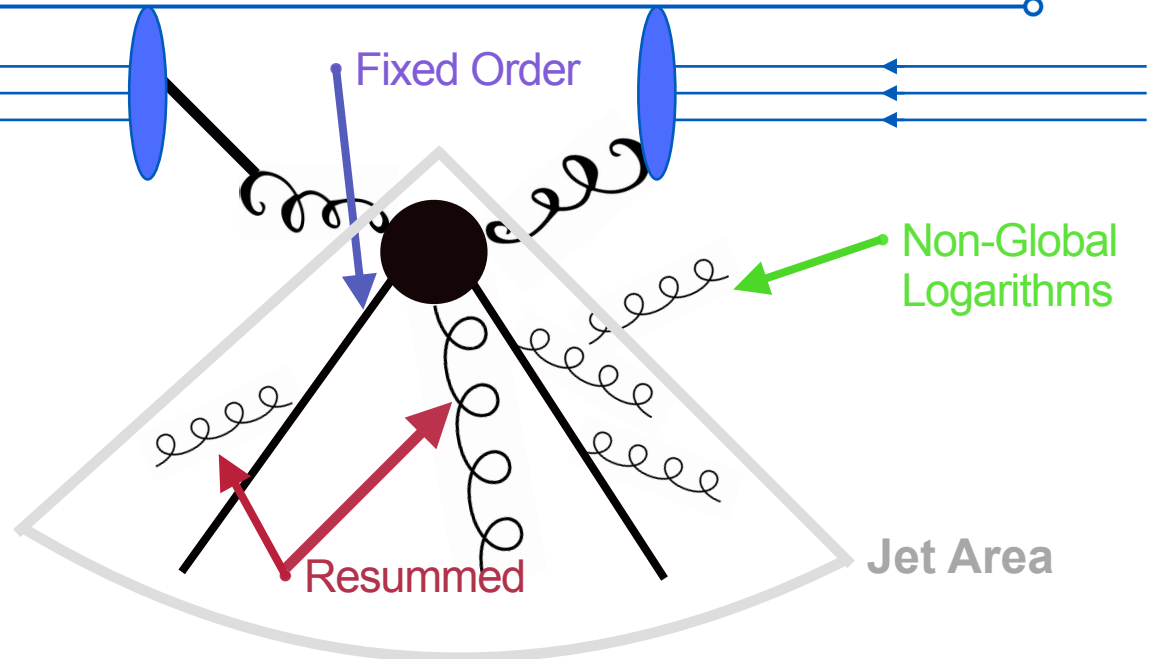
College of Arts and Sciences

Ashley Marie Parker
on behalf of the CMS collaboration

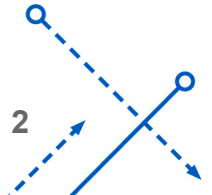
Motivation

- Understand the QCD radiation evolution within jets
- Jet Mass : A simple observable for testing QCD
- Jet Substructure : Helps identify jet flavor and properties
- Theoretical findings are motivating new measurements
- Improve modeling of Jets in monte Carlo Generators

$$e_2 \sim m/p_T$$



C. Frye, A. Larkoski, M. Schwartz, K. Yan, JHEP 07 (2016) 064



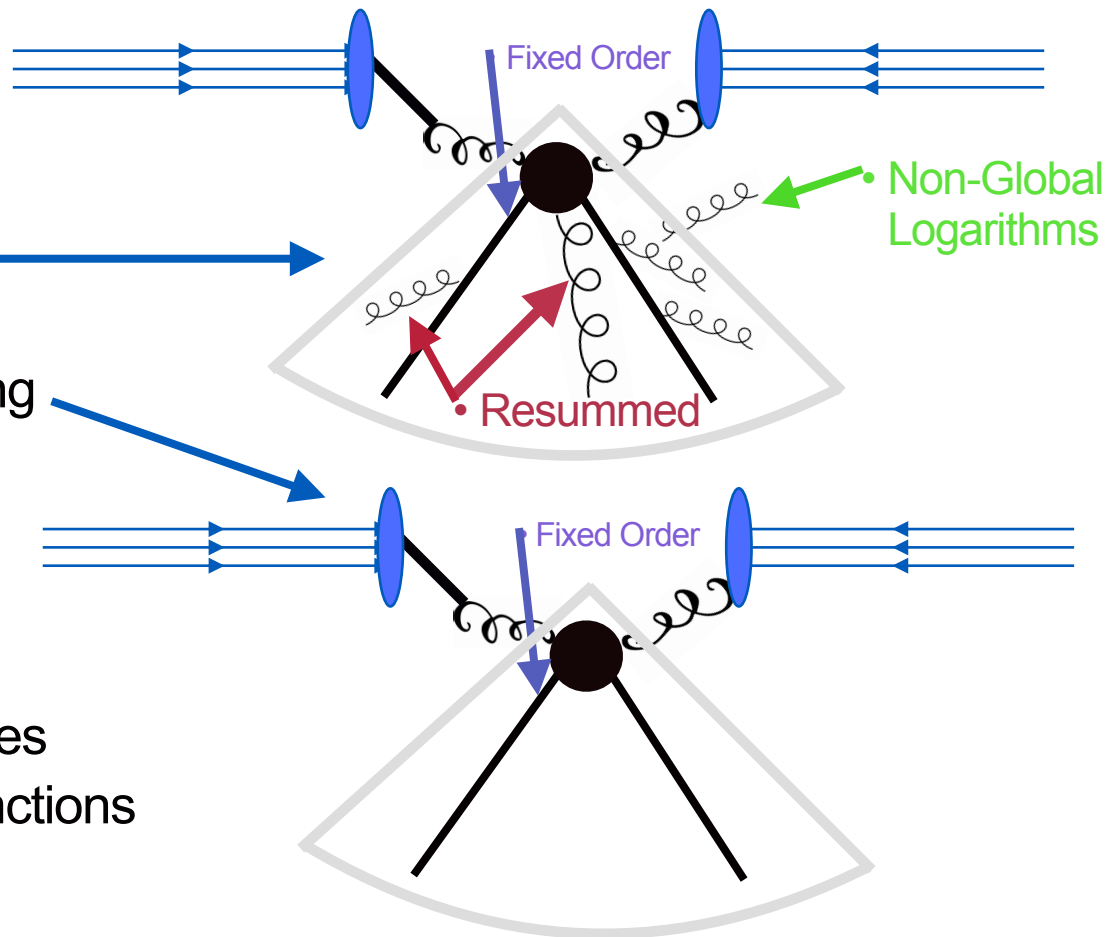
- Studies of the following observables will help us to expand our understanding of jets:

- Jet Mass

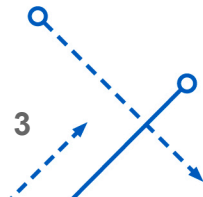
- Ungroomed
- Groomed
 - Soft-Drop Grooming

- Jet Substructure

- Soft-Drop Multiplicity
- N-subjettiness
- Eccentricity
- Generalized Angularities
- Energy Correlation functions



[See Iain's talk for comparable ATLAS measurements](#)



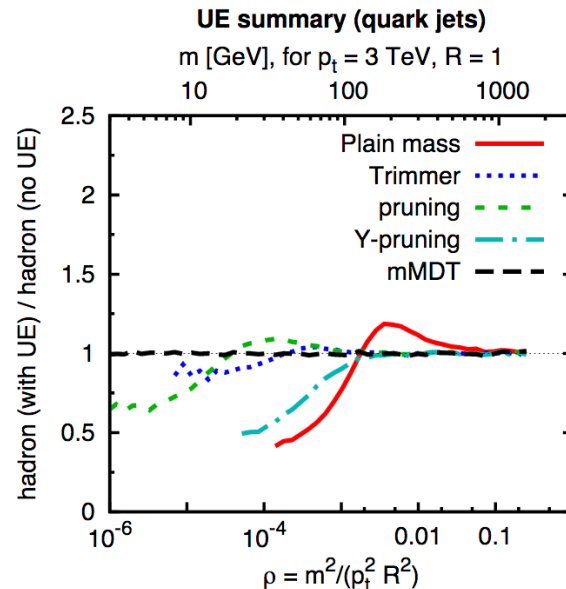
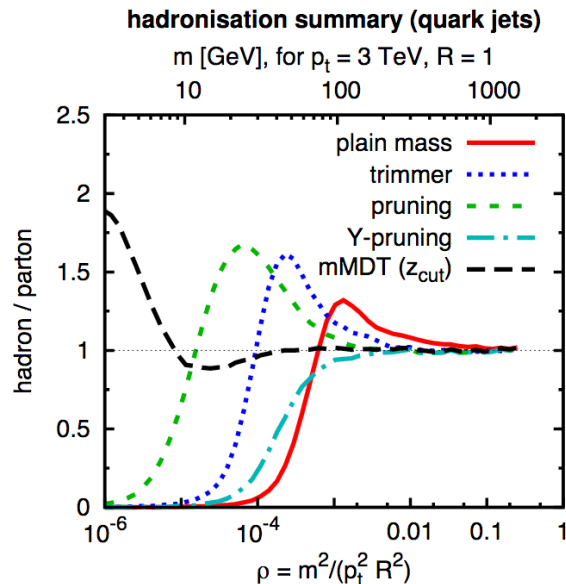
Jet Mass Calculations

- Dimensionless Jet Mass at NLL :
$$\frac{\rho}{\sigma} \frac{d\sigma}{d\rho} \simeq \frac{\alpha_s C_F}{\pi} \left(\ln \frac{1}{\rho} - \frac{3}{4} \right) e^{-\frac{\alpha_s C_F}{2\pi} \left(\ln^2 \frac{1}{\rho} - \frac{3}{2} \ln \frac{1}{\rho} + \mathcal{O}(1) \right)}$$

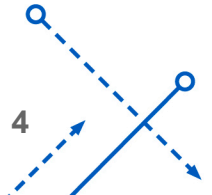
$$\rho \equiv \frac{m^2}{p_t^2 R^2}$$

- Ungroomed jet mass
 - contains contributions from soft and collinear emissions
 - Sudakov peak

- Soft Drop (mMDT) groomed jet mass
 - Removes part of soft and collinear contribution
 - gives theoretically controlled result
 - recently calculated at NNLO + NNLL :



- [JHEP07\(2016\)064](https://arxiv.org/abs/1603.06375)
- [arXiv:1603.06375](https://arxiv.org/abs/1603.06375)



- To remove some of the soft (z_{cut}) and collinear (β) radiation it is useful to groom the jet using **the Soft-Drop procedure**.

[JHEP05\(2014\)146](#)

- Begin with a Jet e.g. Anti-KT
- Re-cluster using the Cambridge/Aachen algorithm

- At each clustering stage:

- Define the momentum fraction:

$$z = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

- Keep the subset if :

$$z > z_{cut} \theta^\beta$$

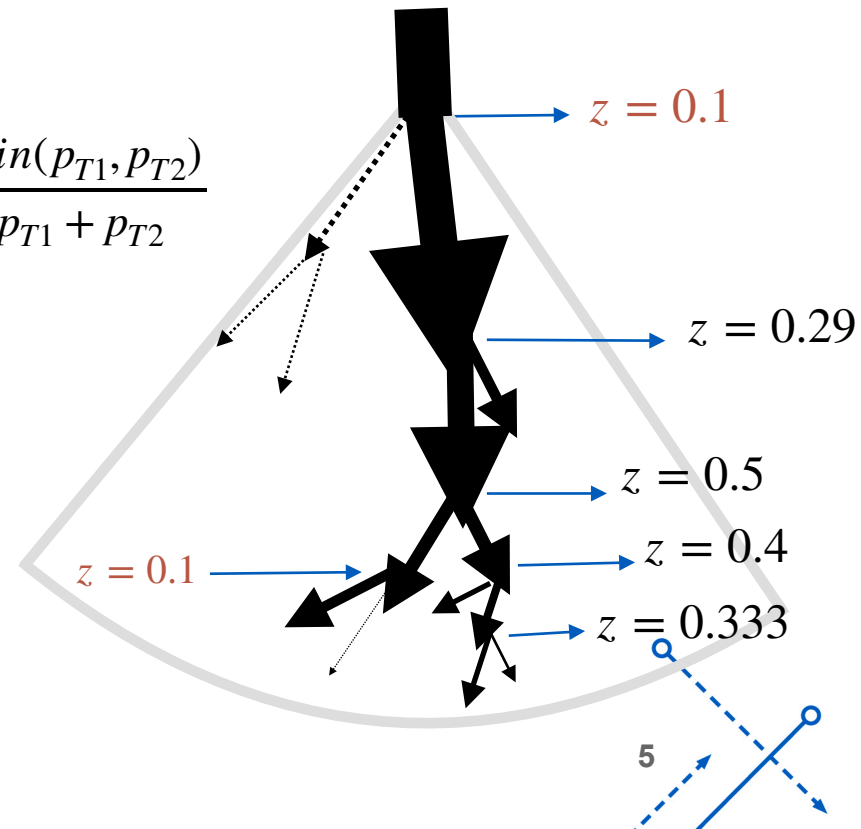
- Where:

$$\theta \equiv \frac{R_{12}}{R}$$

- Imagine the case :

$$z_{cut} = 0.1 \quad \beta = 0$$

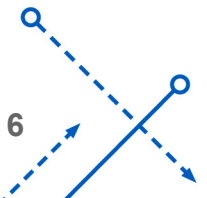
$$z > 0.1$$



- CMS has studied jet mass for events where :
 - At least 2 Anti-KT $R = 0.8$ jets exist
 - Jet $P_t > 200 \text{ GeV}$
 - Jets are similar in momentum : $\frac{(p_{T1} - p_{T2})}{(p_{T1} + p_{T2})} < 0.3$
 - Jets are spatially well separated : $\Delta(\phi_1 - \phi_2) > \frac{\pi}{2}$
 - Measure normalized double ($p_T, [m_u || m_g]$) differential production cross section:

$$\frac{1}{d\sigma/dp_T} \frac{d^2\sigma}{dp_T dm} (1/\text{GeV})$$

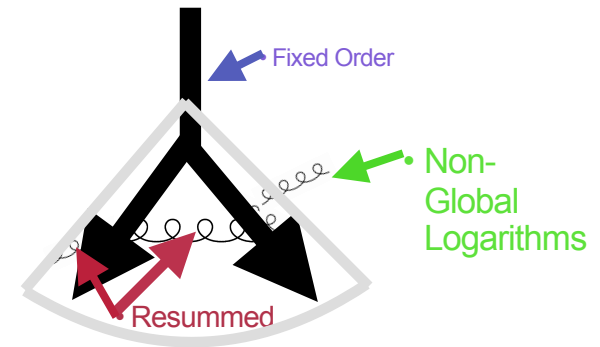
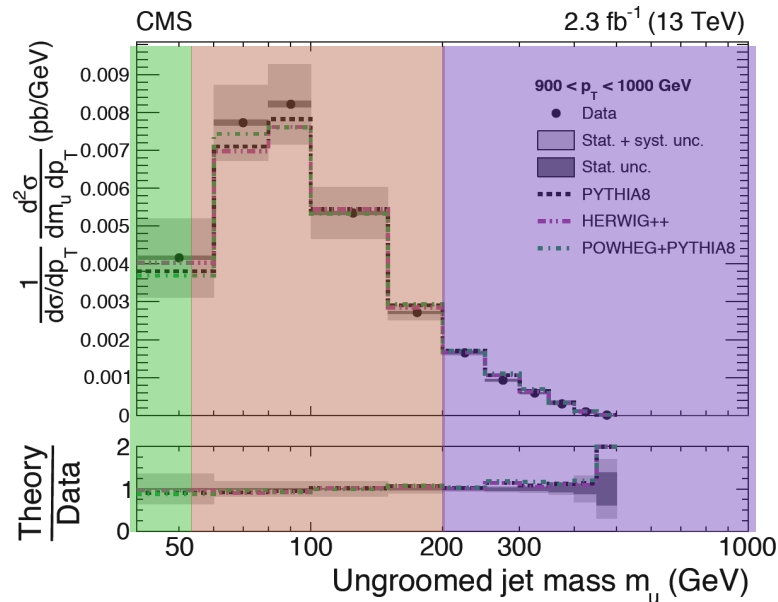
- This yields a jet sample which is quark-gluon admixture enriched



DiJet Mass Measurement at CMS

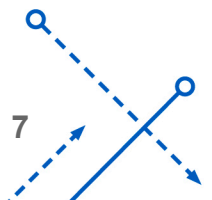
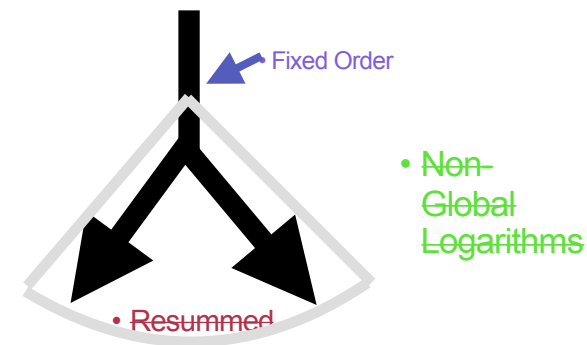
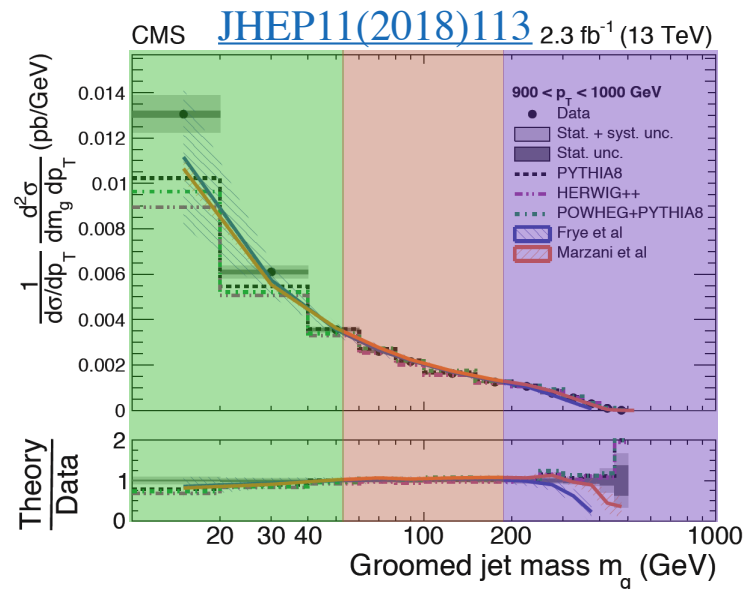
Ungroomed

- Larger Uncertainties below Sudakov Peak



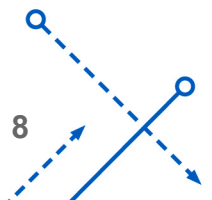
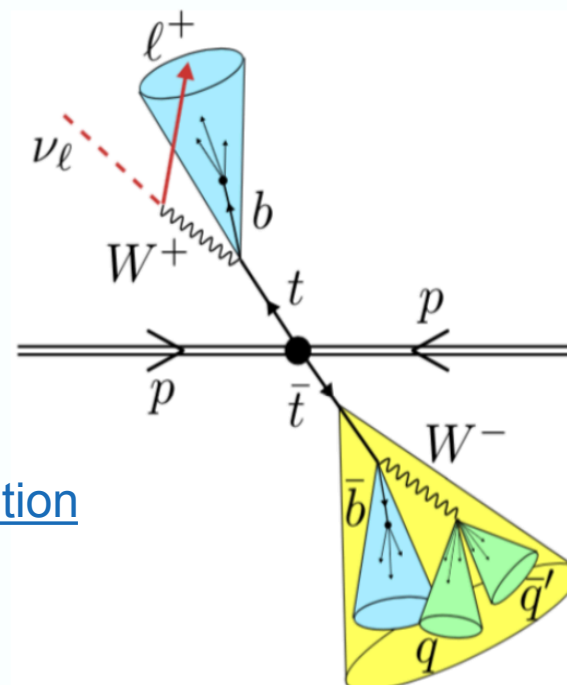
Soft-Drop Groomed $\beta = 0$ $z_{cut} = 0.1$

- Disagreement at low and high mass
- Smaller uncertainties than ungroomed



- CMS has studied jet substructure observables for events where :
 - At least 4 jets with $R = 0.4$ and $p_T > 30 \text{ GeV}$
 - At least 2 jets b-tagged with CSVv2 algorithm
 - At least 2 un-tagged jets
 - Sum of their masses within 15 GeV of W mass range
 - Exactly 1 isolated electron (muon) exists with: $p_T > 34 \text{ (26) GeV}$
- This yields bottom quark enriched as well as light quark enriched samples
- Observables studied :
 - Soft-Drop Multiplicity
 - Generalized Angularities
 - N-subjettiness
 - Energy Correlation Functions
 - Eccentricity
 - Strong coupling constant extraction

[See Juska's talk for more information](#)

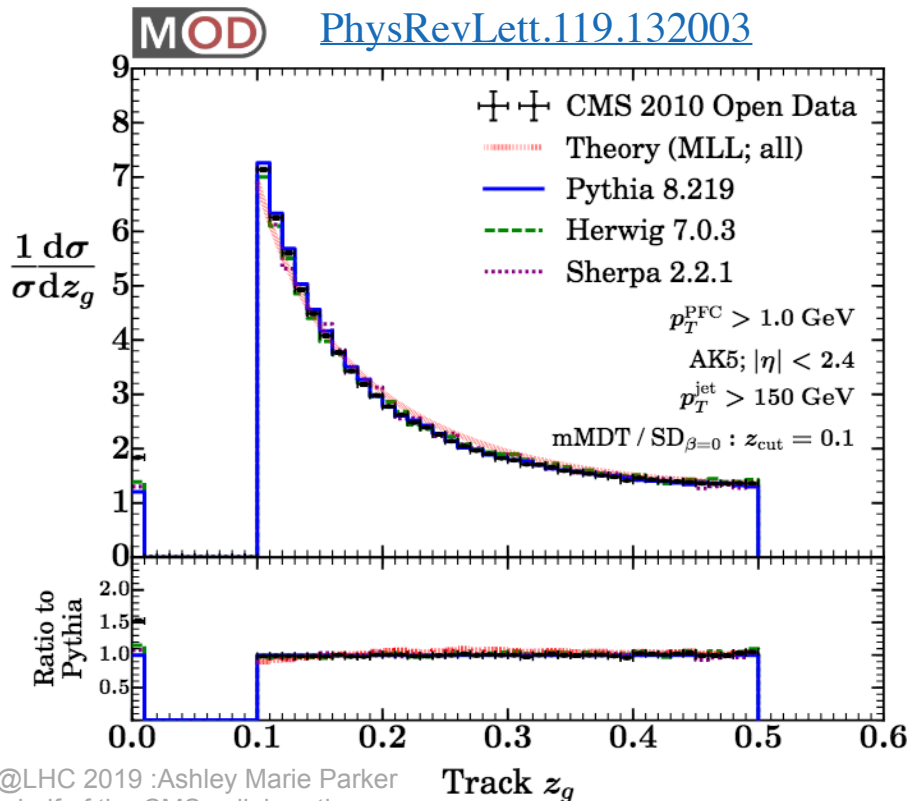
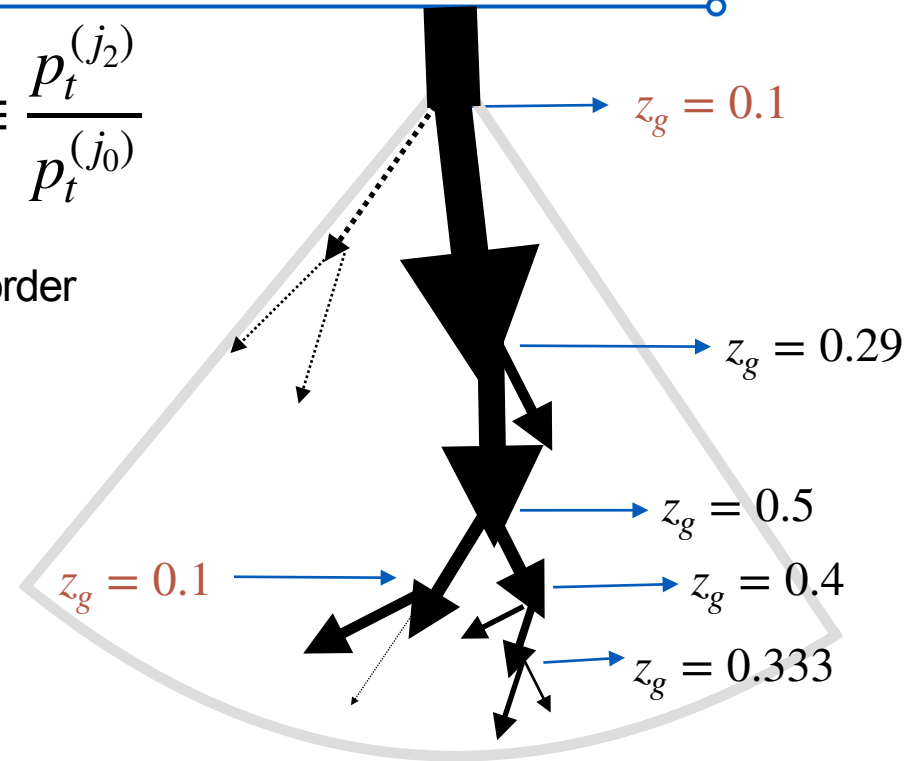


Jet Substructure Observables

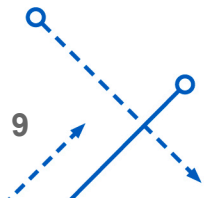
• Groomed Momentum Fraction

$$z_g \equiv \frac{p_t^{(j_2)}}{p_t^{(j_0)}}$$

- Closely related to QCD splitting function
- Independent of strong coupling constant to 1st order



$$p(z_g) \simeq \frac{2 \frac{z_g}{1-z_g} + 2 \frac{1-z_g}{z_g} + 1}{\frac{3}{2} (2z_{\text{cut}} - 1) + 2 \log \frac{1-z_{\text{cut}}}{z_{\text{cut}}}}$$



Jet Substructure Observables

- Soft Drop Multiplicity

- Number of branchings in clustering tree for which:

$$\Delta R_g > \theta_{\text{cut}} \quad \& \quad z_g > z_{\text{cut}} \left(\frac{\Delta R_g}{R_0} \right)^\beta$$

[PhysRevD.98.092014](https://arxiv.org/abs/1409.0920)

- For simplicity imagine the case :

$$\beta = 0 \quad z_{\text{cut}} = 0.1 \quad \theta_{\text{cut}} = 0$$

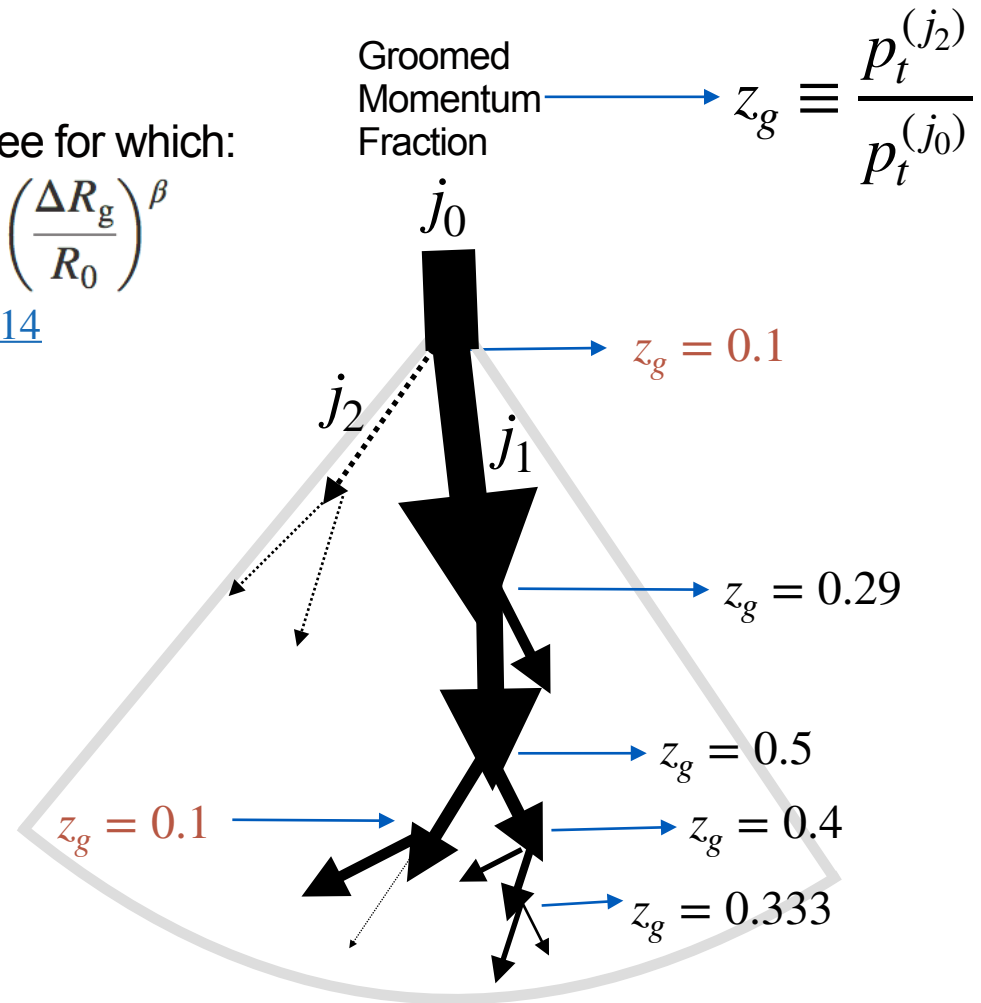
- This simplifies to just :

$$z_g > 0.1$$

- In this example :

$$n_{SD} = 4$$

- Strong FSR dependence

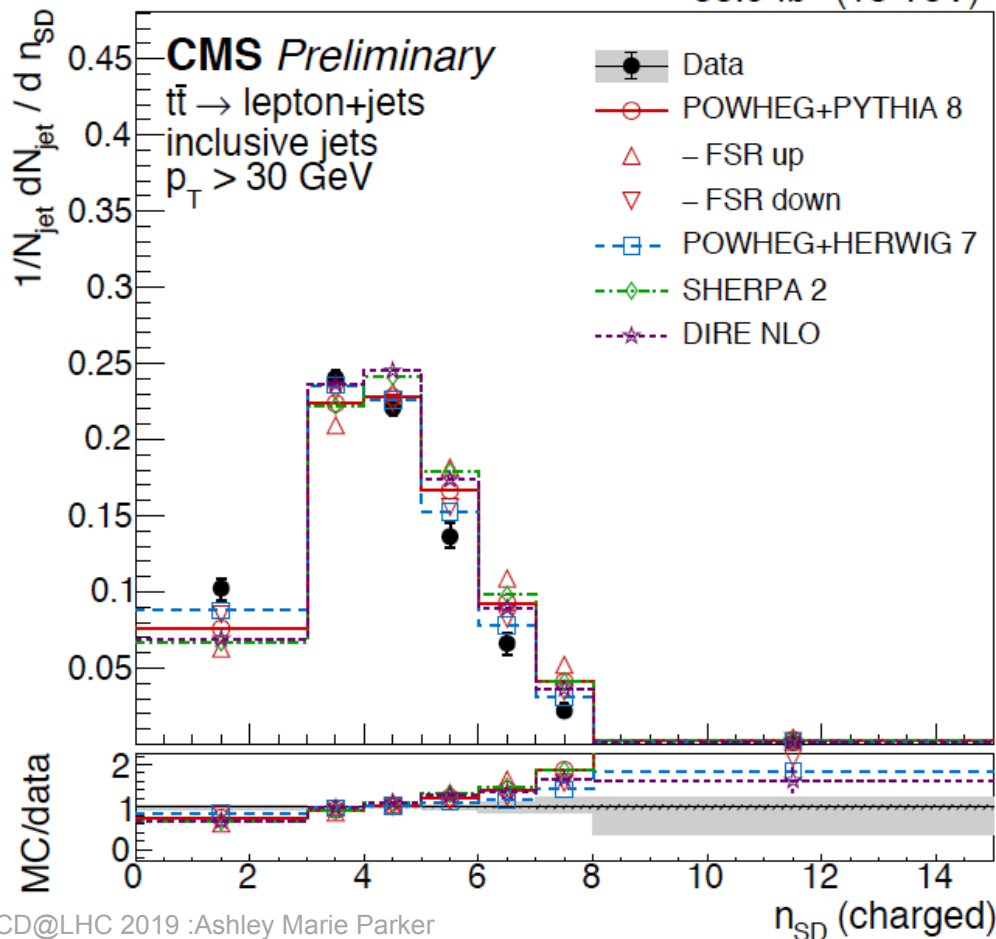


• Soft Drop Multiplicity

- Number of branchings in clustering tree for which: $\Delta R_g > \theta_{\text{cut}}$ & $z_g > z_{\text{cut}} \left(\frac{\Delta R_g}{R_0} \right)^\beta$

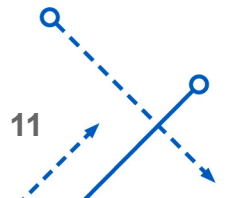
[PhysRevD.98.092014](#)

35.9 fb⁻¹ (13 TeV)



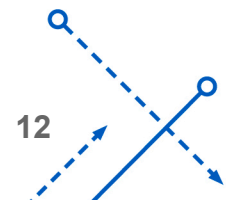
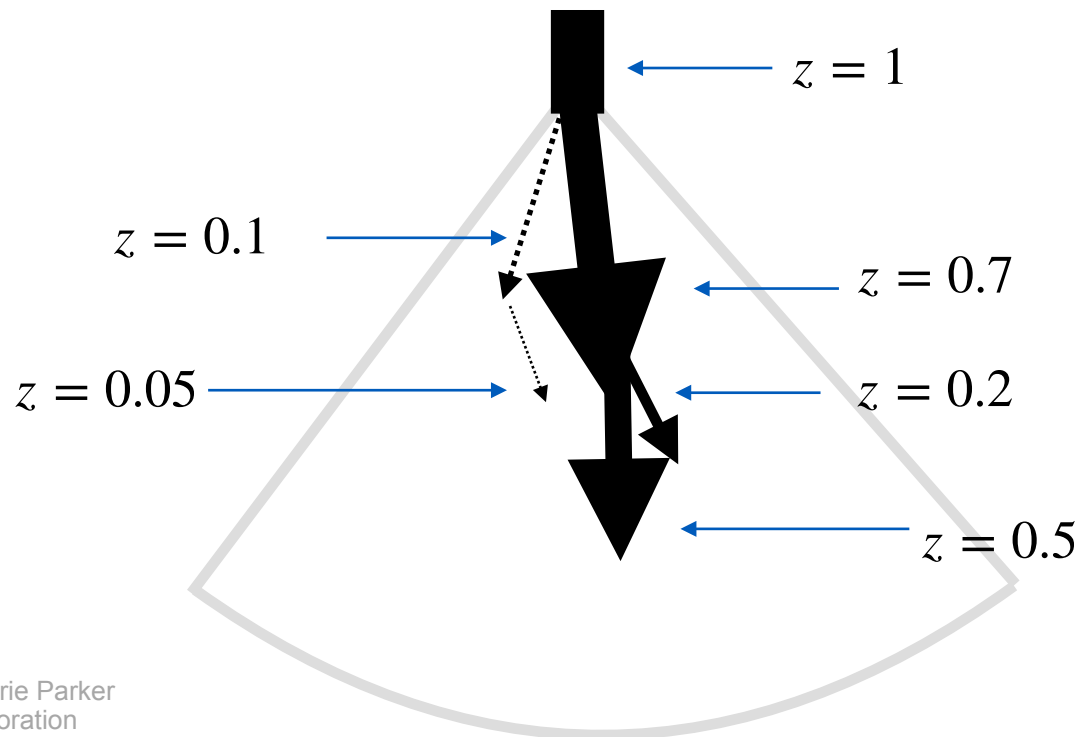
- Shown here for :
 - semi-leptonic top-antitop events
 - Jet radius $R = 0.4$
 - Soft-Drop parameters :

$$z_{\text{cut}} = 0.007, \beta = -1, \theta_{\text{cut}} = 0.$$



Jet Substructure Observables

- Generalized Angularities $\lambda_{\beta}^{\kappa} = \sum_i z_i^{\kappa} \left(\frac{\Delta R(i, \hat{n}_r)}{R} \right)^{\beta}$ $\lambda_0^0 = N$
- Momentum fraction per particle in jet : $z_i = p_T^i / \sum_i p_T^i$ [PhysRevD.98.092014](https://arxiv.org/abs/1409.0920)

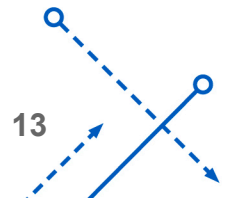
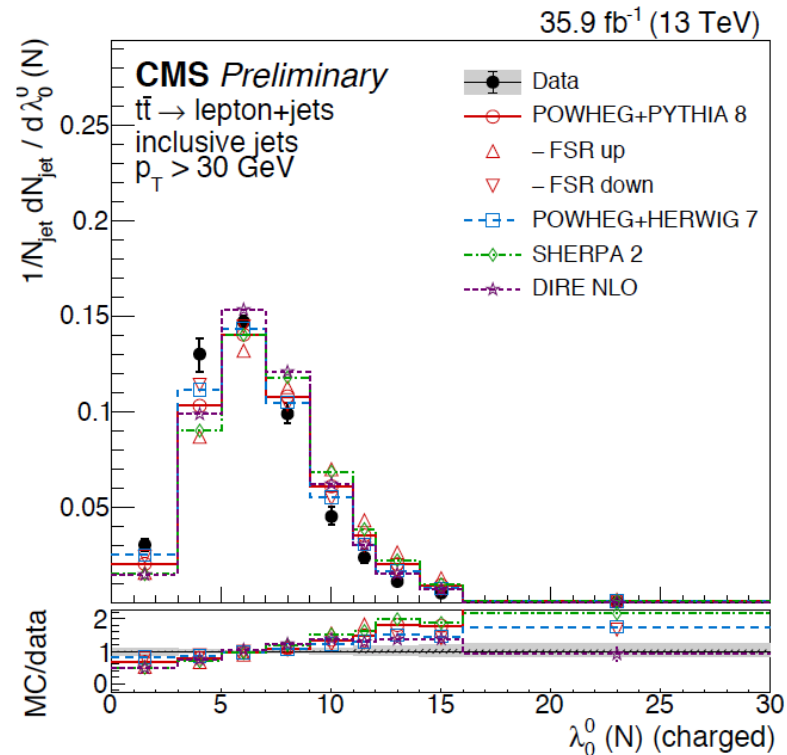
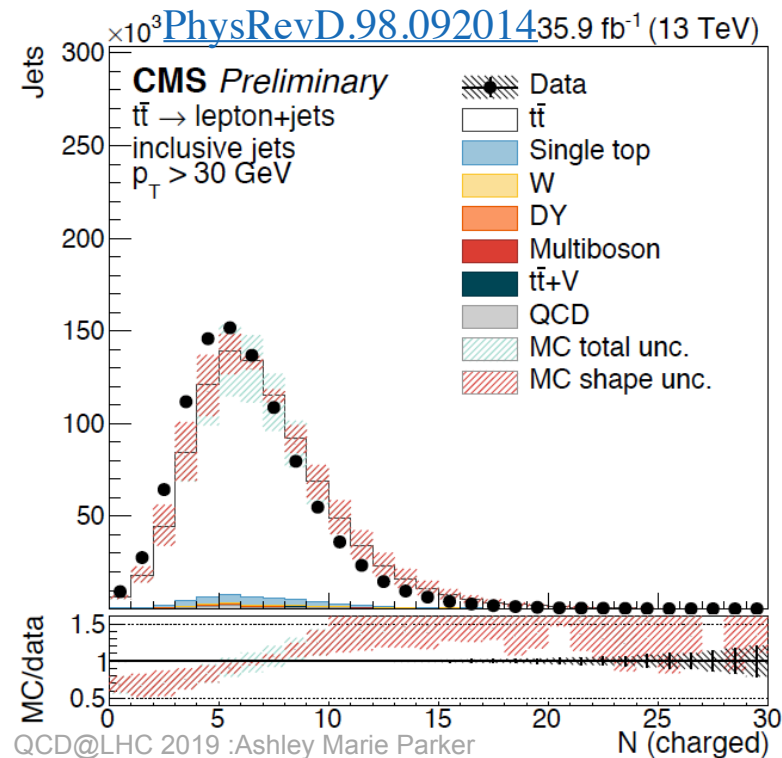


• Generalized Angularities

$$\lambda_{\beta}^{\kappa} = \sum_i z_i^{\kappa} \left(\frac{\Delta R(i, \hat{n}_r)}{R} \right)^{\beta} \quad \lambda_0^0 = N_i$$

• Momentum fraction per particle in jet :

$$z_i = p_T^i / \sum_i p_T^i$$



Generalized Angularities

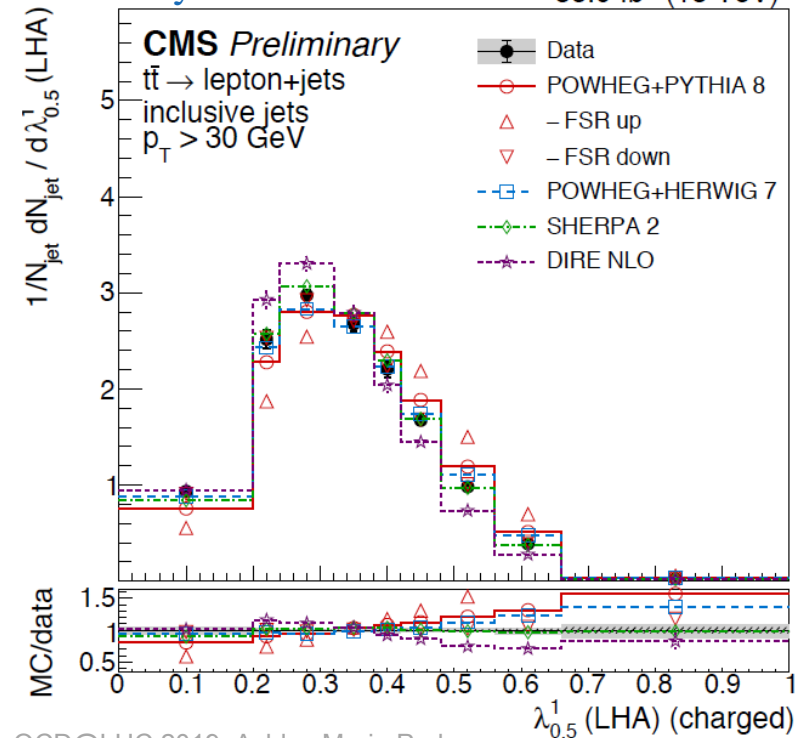
$$\lambda_{\beta}^{\kappa} = \sum_i z_i^{\kappa} \left(\frac{\Delta R(i, \hat{n}_r)}{R} \right)^{\beta}$$

- Momentum fraction per particle in jet :

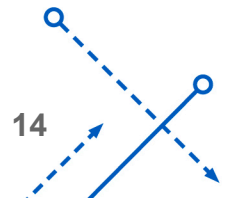
$$z_i = p_T^i / \sum_i p_T^i$$

[PhysRevD.98.092014](#)

35.9 fb⁻¹ (13 TeV)



- Les Houches Angularity (LHA)
 - Mass related to jet thrust
 - Width related to Jet widening



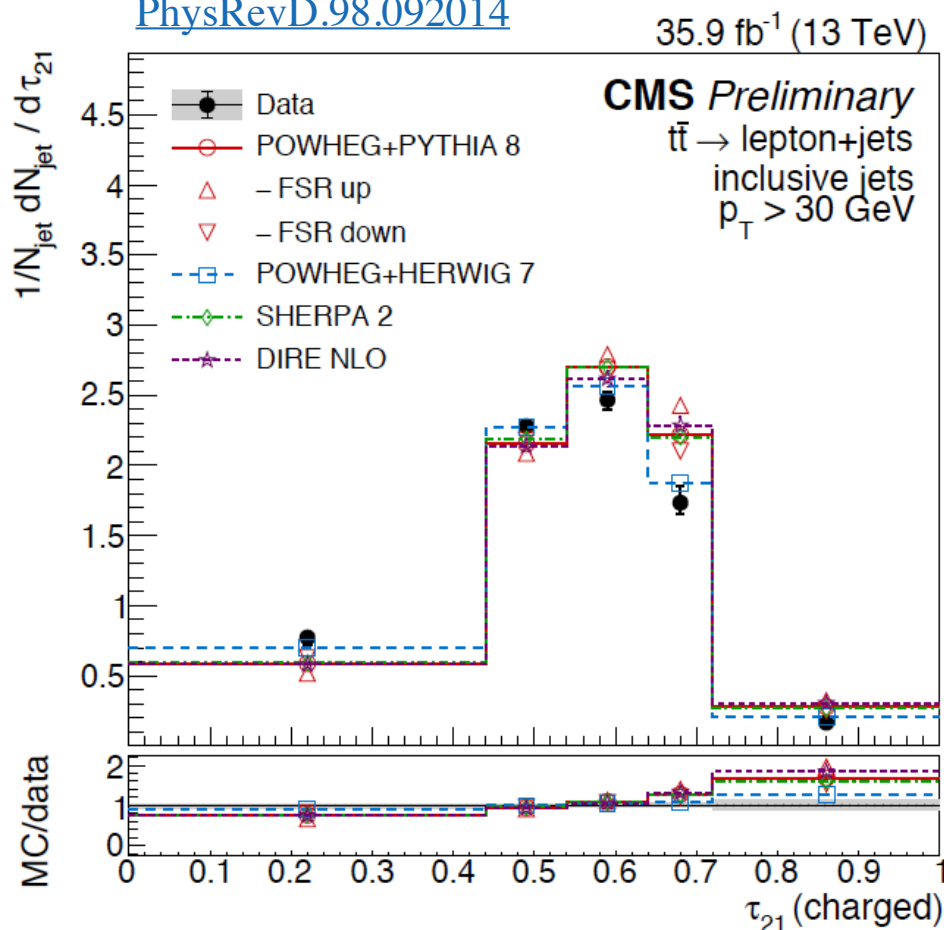
[See Davide's talk for more information](#)

•N-subjettiness

$$\tau_N^{(\beta)} = \frac{1}{d_0} \sum_i p_{T,i} \min \left\{ (\Delta R_{1,i})^\beta, (\Delta R_{2,i})^\beta, \dots, (\Delta R_{N,i})^\beta \right\}$$

$$d_0 = \sum_i p_{T,i} (R_0)^\beta$$

[PhysRevD.98.092014](#)

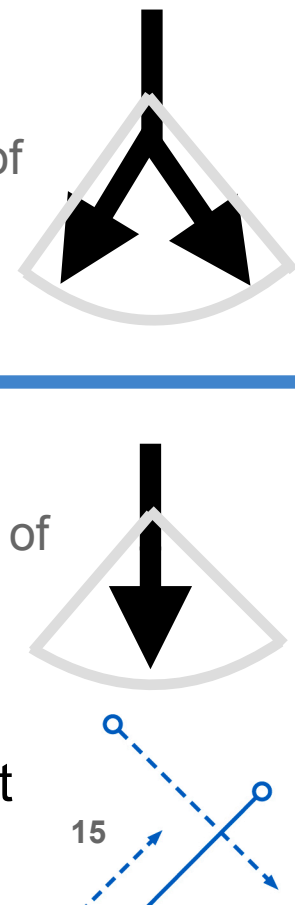


“Probability” of

$$\tau_{21} =$$

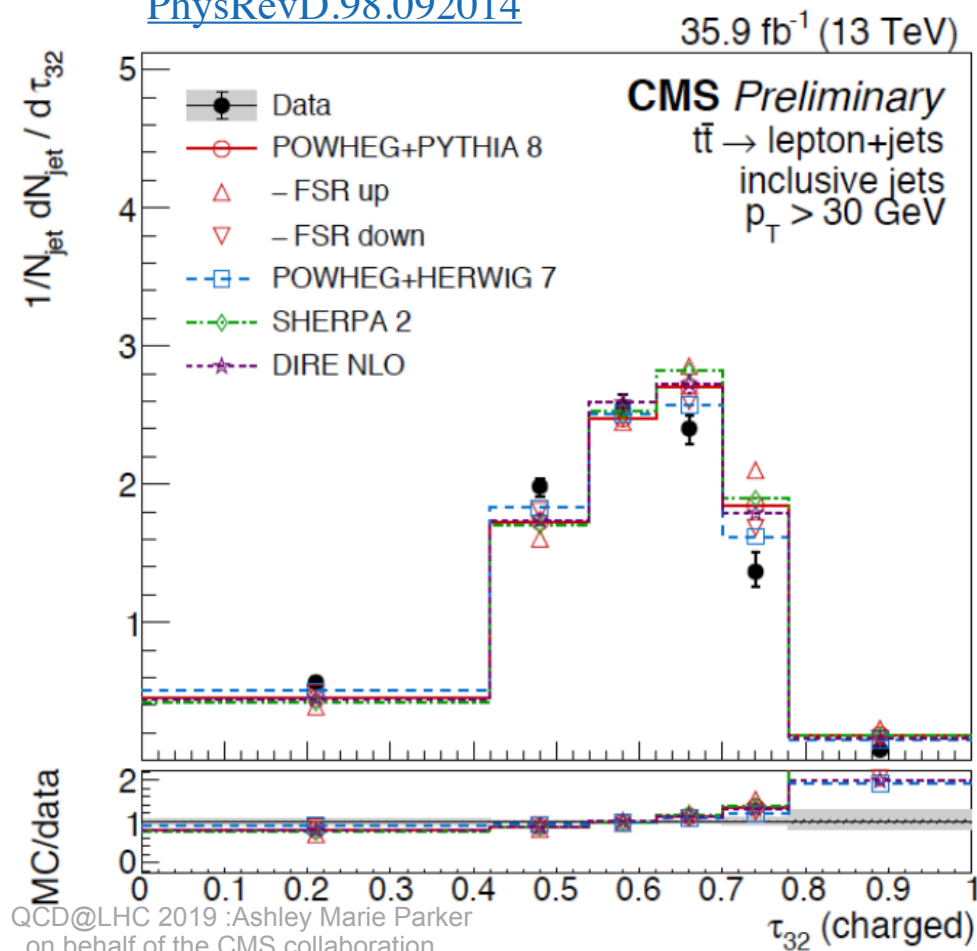
“Probability” of

- Identify jets with a 2 prong structure
- Useful for W/H/Z jet identification



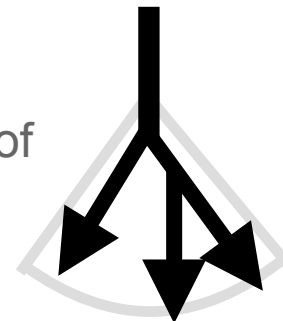
•N-subjettiness

[PhysRevD.98.092014](#)

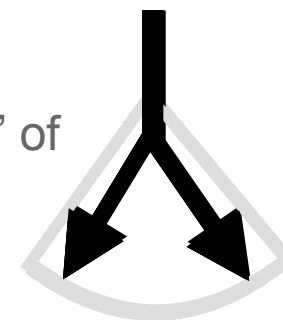


$$\tau_{32} =$$

“Probability” of



“Probability” of

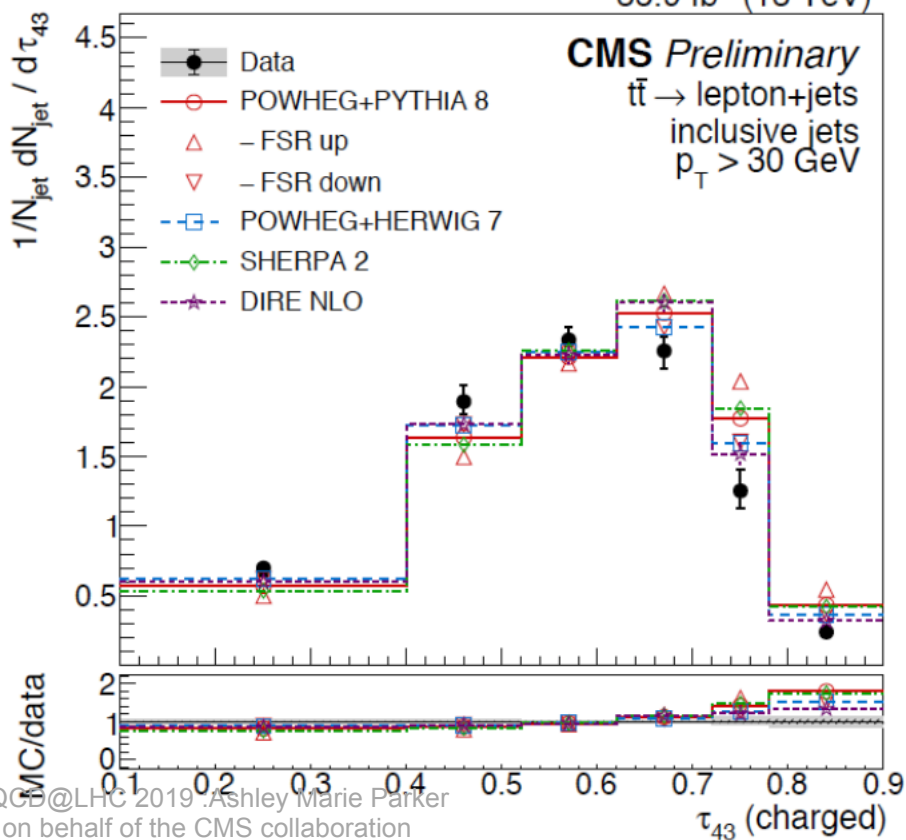


- Identify jets with a 3 prong structure
- Useful for Top jet identification

•N-subjettiness

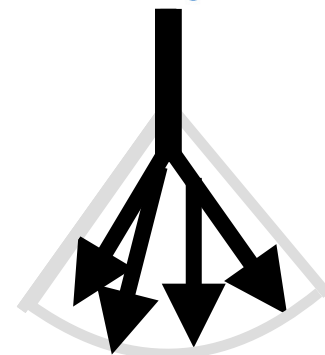
PhysRevD.98.092014

35.9 fb⁻¹ (13 TeV)

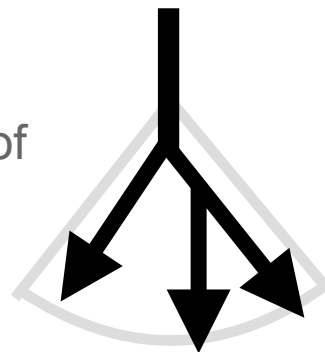


$$\tau_{43} =$$

“Probability” of



“Probability” of



- Identify jets with a 4 prong structure
- Useful for H→WW

See Ian's talk for more on 3-point correlations

• Energy Correlation Functions

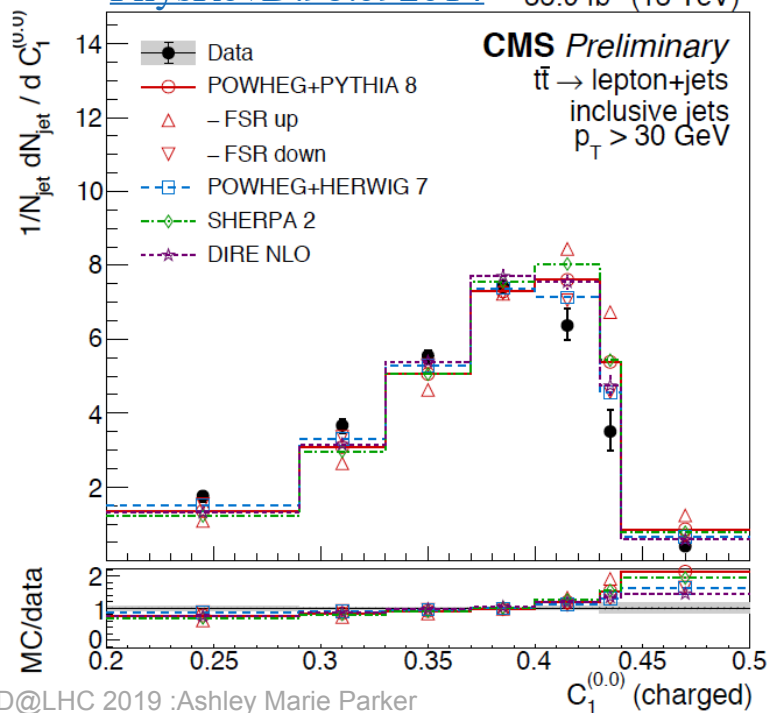
$$\text{ECF}(N, \beta) = \sum_{i_1 < i_2 < \dots < i_N} \left(\prod_{a=1}^N p_{T_{i_a}} \right) \left(\prod_{b=1}^{N-1} \prod_{c=b+1}^N \Delta R_{i_b i_c} \right)^\beta$$

- Similar to N-subjettiness however there is no need to pick a subjet axis
- C_N sensitive to (N-1) pronged substructure of a jet

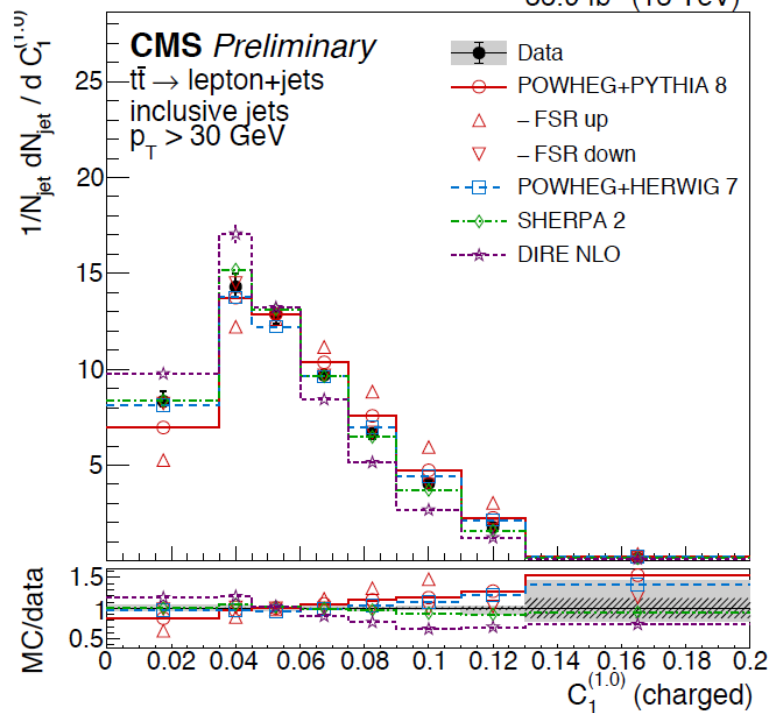
$$C_N^{(\beta)} = \frac{\text{ECF}(N+1, \beta) \text{ECF}(N-1, \beta)}{\text{ECF}(N, \beta)^2}$$

[PhysRevD.98.092014](#)

35.9 fb⁻¹ (13 TeV)



35.9 fb⁻¹ (13 TeV)



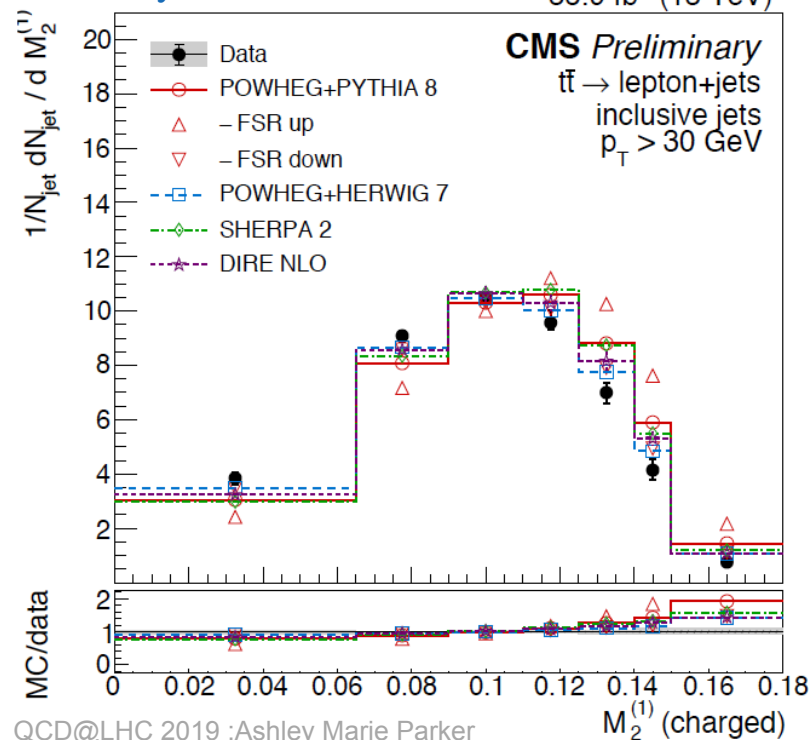
• Energy Correlation Functions

$$M_i^{(\beta)} = \frac{{}_1e_{i+1}^{(\beta)}}{{}_1e_i^{(\beta)}}, \quad N_i^{(\beta)} = \frac{2e_{i+1}^{(\beta)}}{({}_1e_i^{(\beta)})^2}$$

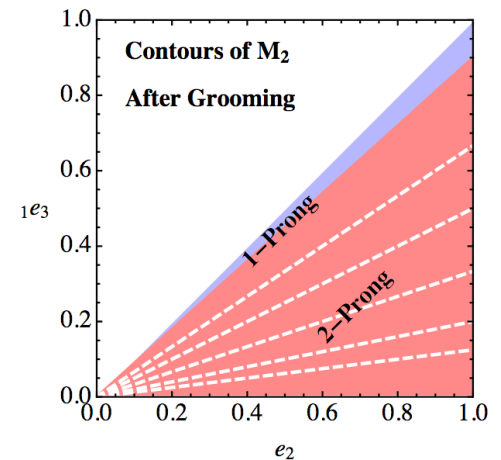
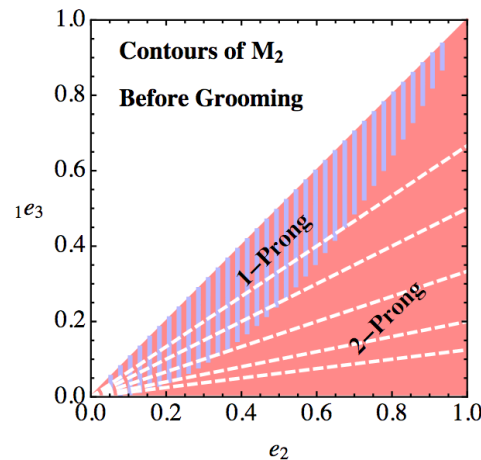
$${}_ve_n^{(\beta)} = \sum_{1 \leq i_1 < i_2 < \dots < i_n \in j} z_{i_1} z_{i_2} \dots z_{i_n} \times \prod_{m=1}^v \min_{s < t \in \{i_1, i_2, \dots, i_n\}}^{(m)} \{\Delta R_{st}^\beta\}$$

[PhysRevD.98.092014](#)

35.9 fb⁻¹ (13 TeV)



[JHEP12\(2016\)153](#)



• Useful for jet shape discrimination only after grooming

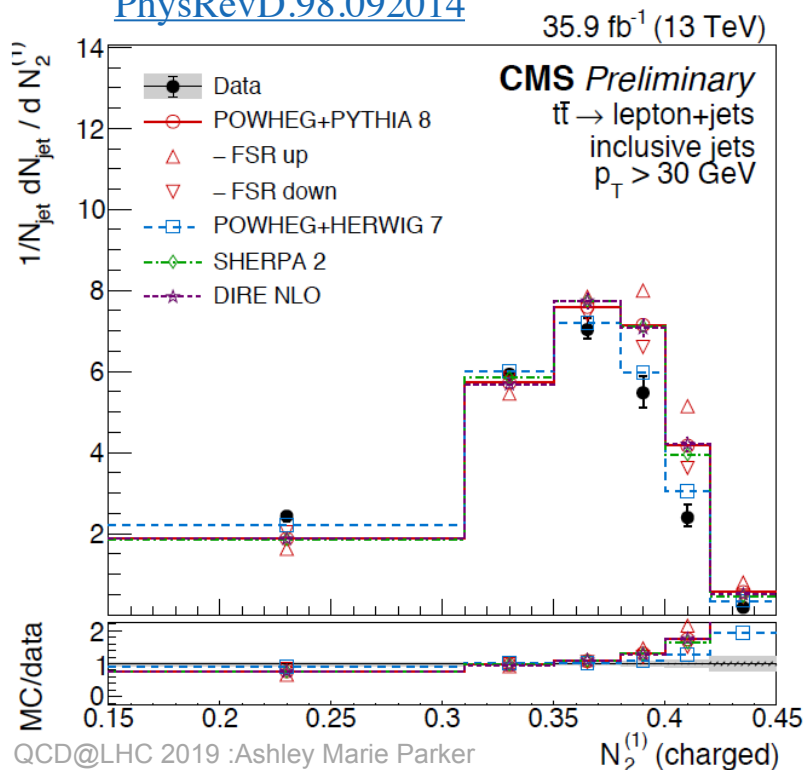


•Energy Correlation Function Ratios

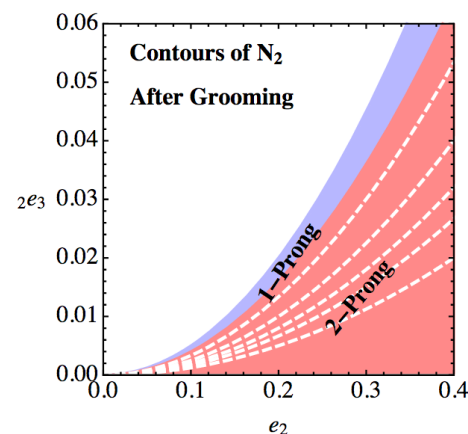
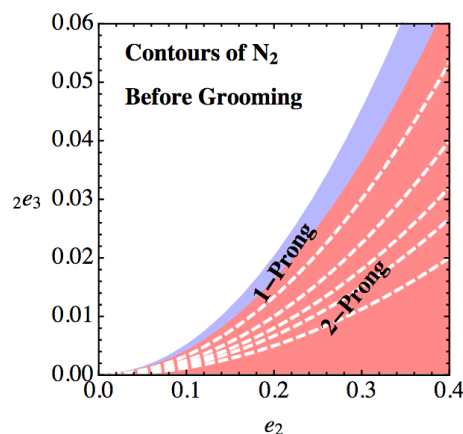
$$N_i^{(\beta)} = \frac{2e_{i+1}^{(\beta)}}{(1e_i^{(\beta)})^2}$$

$$v e_n^{(\beta)} = \sum_{1 \leq i_1 < i_2 < \dots < i_n \in j} z_{i_1} z_{i_2} \dots z_{i_n} \times \prod_{m=1}^v \min_{s < t \in \{i_1, i_2, \dots, i_n\}}^{(m)} \{\Delta R_{st}^\beta\}$$

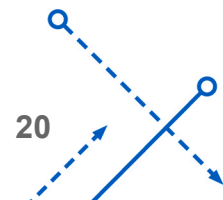
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[JHEP12\(2016\)153](#)

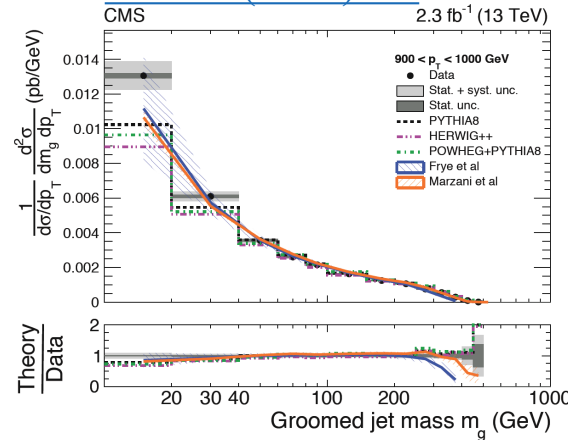


- Useful for jet shape discrimination regardless of grooming



Jet Observables Studied by CMS: Summary

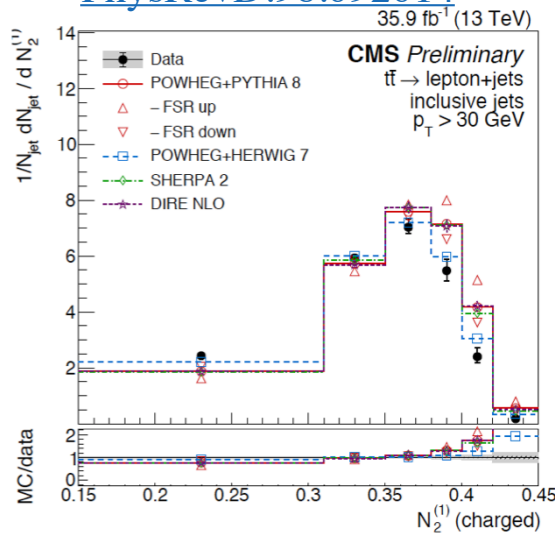
[JHEP11\(2018\)113](#)



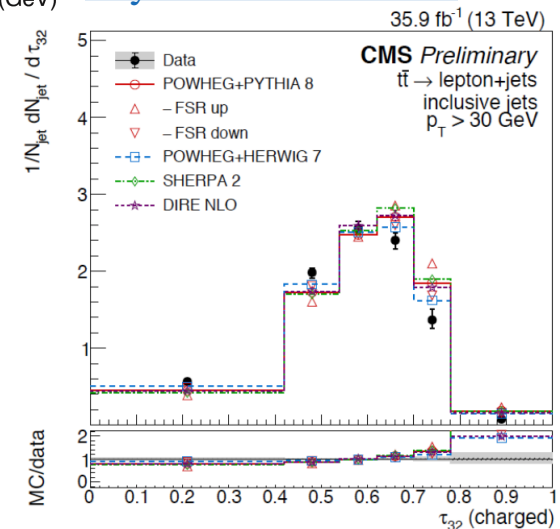
- Jet Mass
 - Soft-Drop Grooming
- N-subjettiness
 - τ_{32}
- Energy Correlation functions
 -

$$N_2^1 = \frac{2e_{i+1}^1}{(1e_i^1)^2}$$

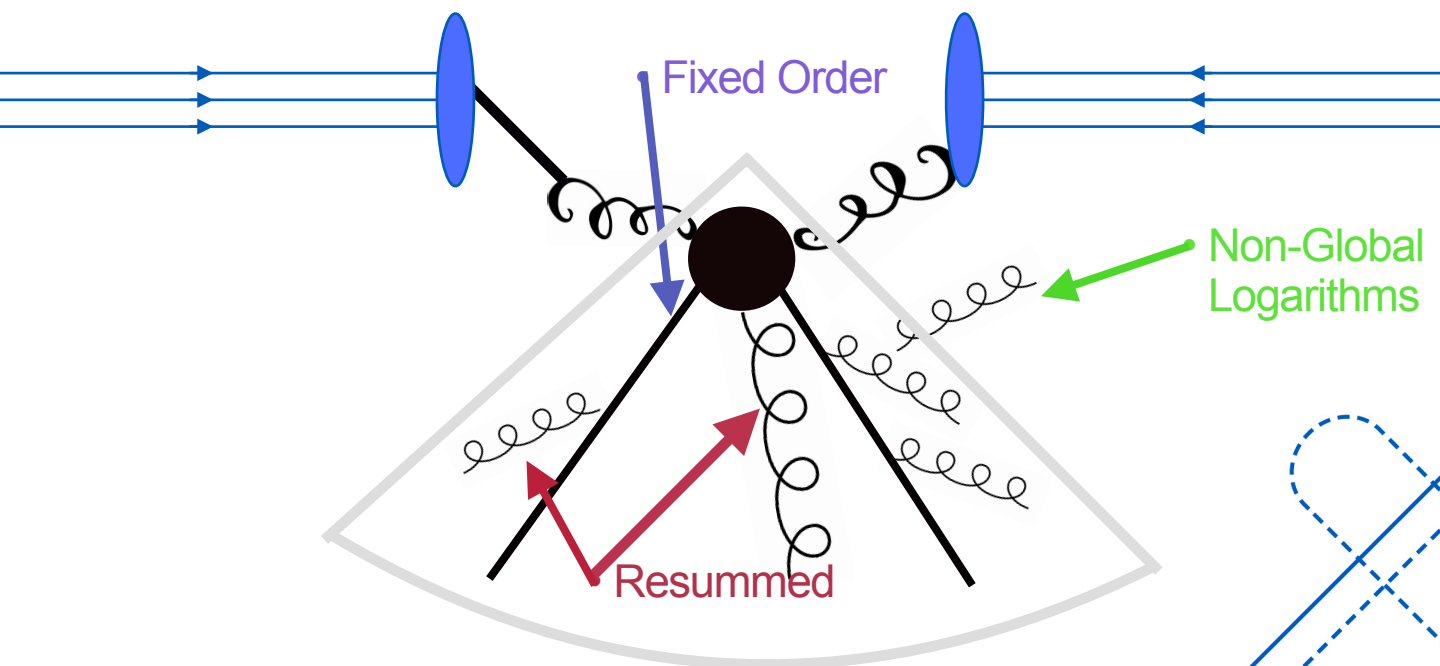
[PhysRevD.98.092014](#)



[PhysRevD.98.092014](#)



THANK YOU FOR YOUR ATTENTION!



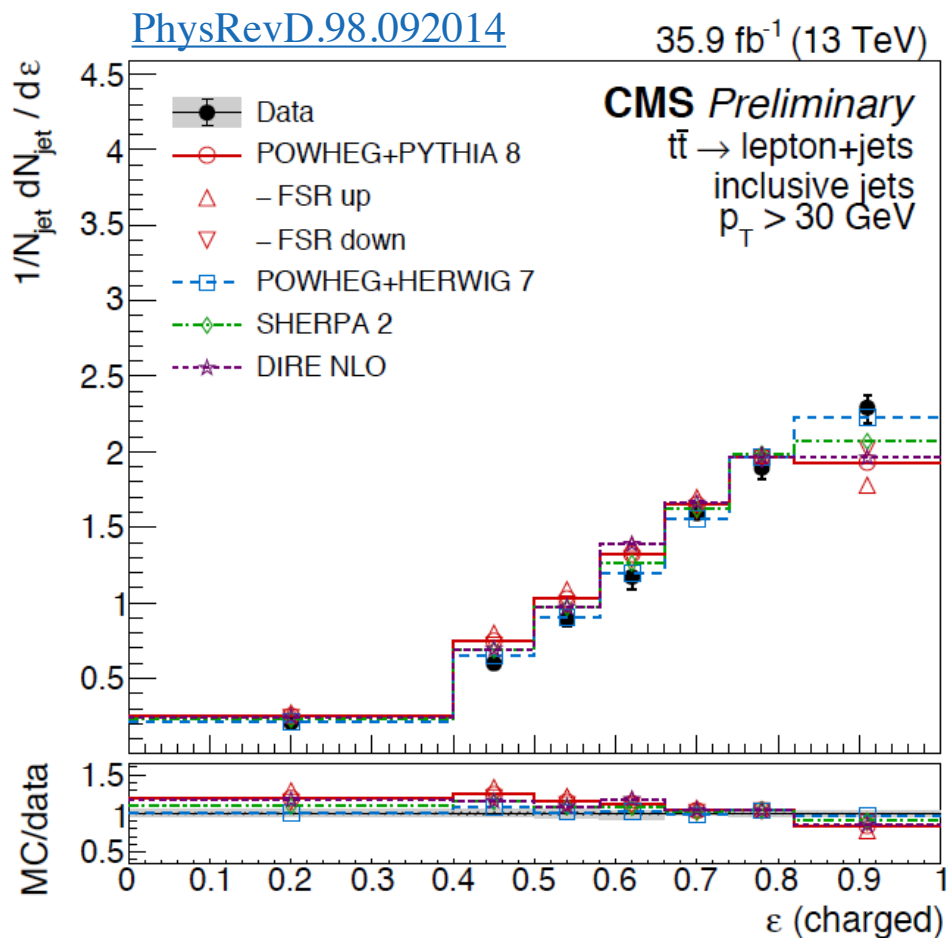
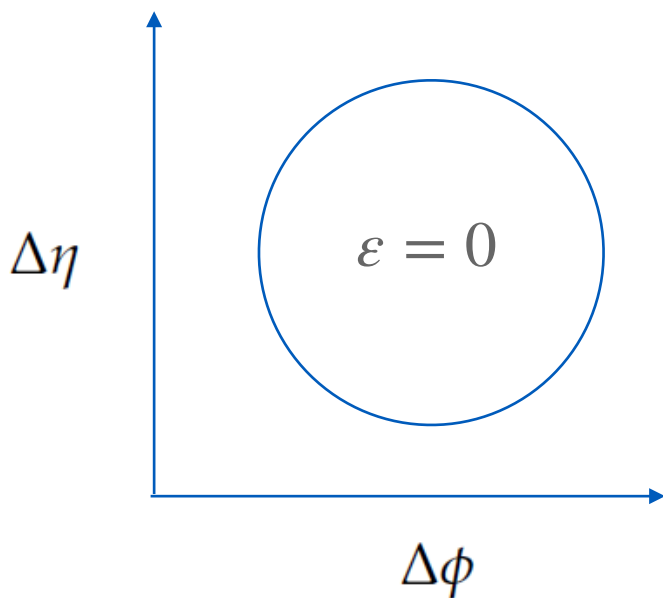


BACKUP SLIDES

•Eccentricity

$$\varepsilon = 1 - v_{\min} / v_{\max}$$

$$M = \sum_i E_i \times \begin{pmatrix} (\Delta\eta_{i,\hat{n}_r})^2 & \Delta\eta_{i,\hat{n}_r} \Delta\phi_{i,\hat{n}_r} \\ \Delta\phi_{i,\hat{n}_r} \Delta\eta_{i,\hat{n}_r} & (\Delta\phi_{i,\hat{n}_r})^2 \end{pmatrix}$$



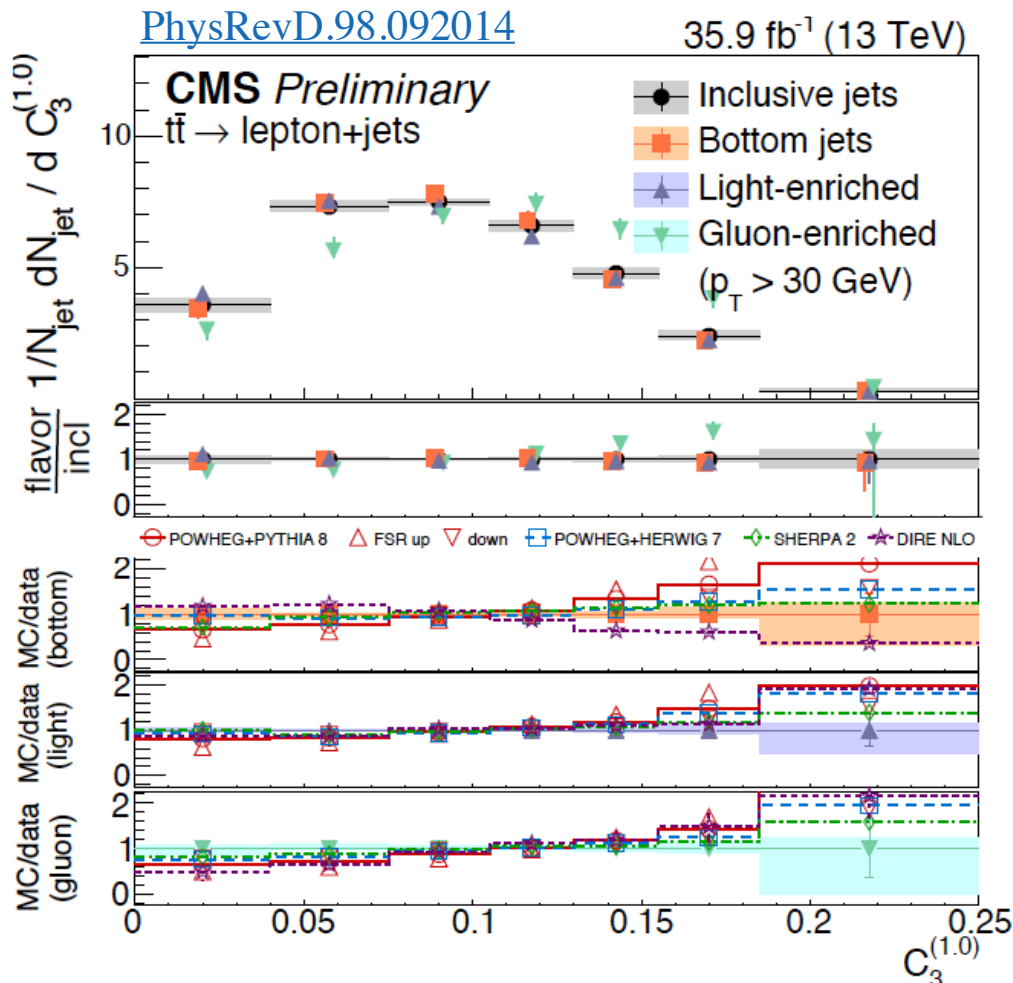
Jet Flavor Variations

- We can analyze different channels to obtain samples enriched with each jet flavor

- Top / Bottom Jets : $t\bar{t}$ events
- Gluon Jets : Dijet events

Jet Flavors

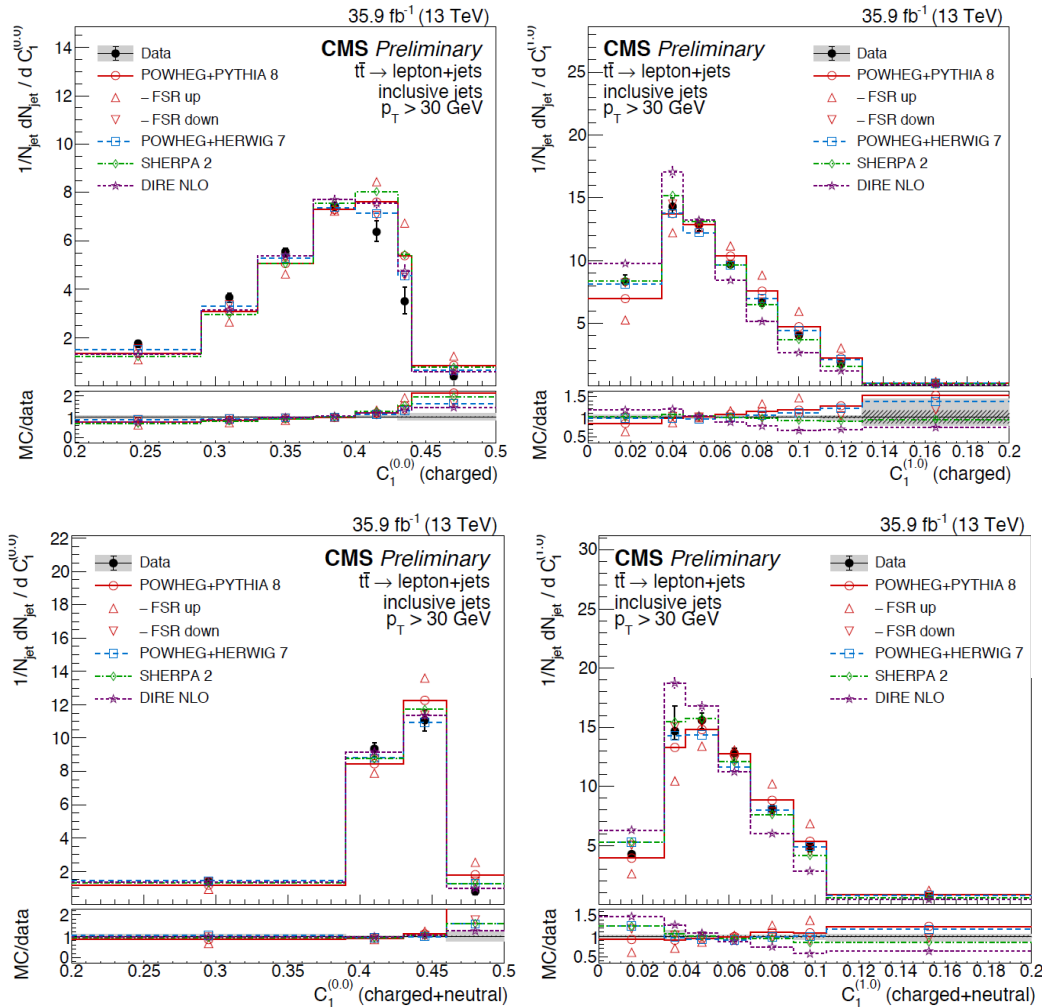
- Bottom Jets
- Light Quark Jets
- Gluon Jets



$$C_3^1 = \frac{ECF(4,1)ECF(2,1)}{ECF(3,1)^2}$$



•Energy Correlation Functions



•Charged

$$C_N^{(\beta)} = \frac{\text{ECF}(N+1, \beta) \text{ECF}(N-1, \beta)}{\text{ECF}(N, \beta)^2}$$

[PhysRevD.98.092014](https://arxiv.org/abs/1409.0924)

$$\text{ECF}(N, \beta) = \sum_{i_1 < i_2 < \dots < i_N} \left(\prod_{a=1}^N p_{T_{i_a}} \right) \left(\prod_{b=1}^{N-1} \prod_{c=b+1}^N \Delta R_{i_b i_c} \right)^\beta$$

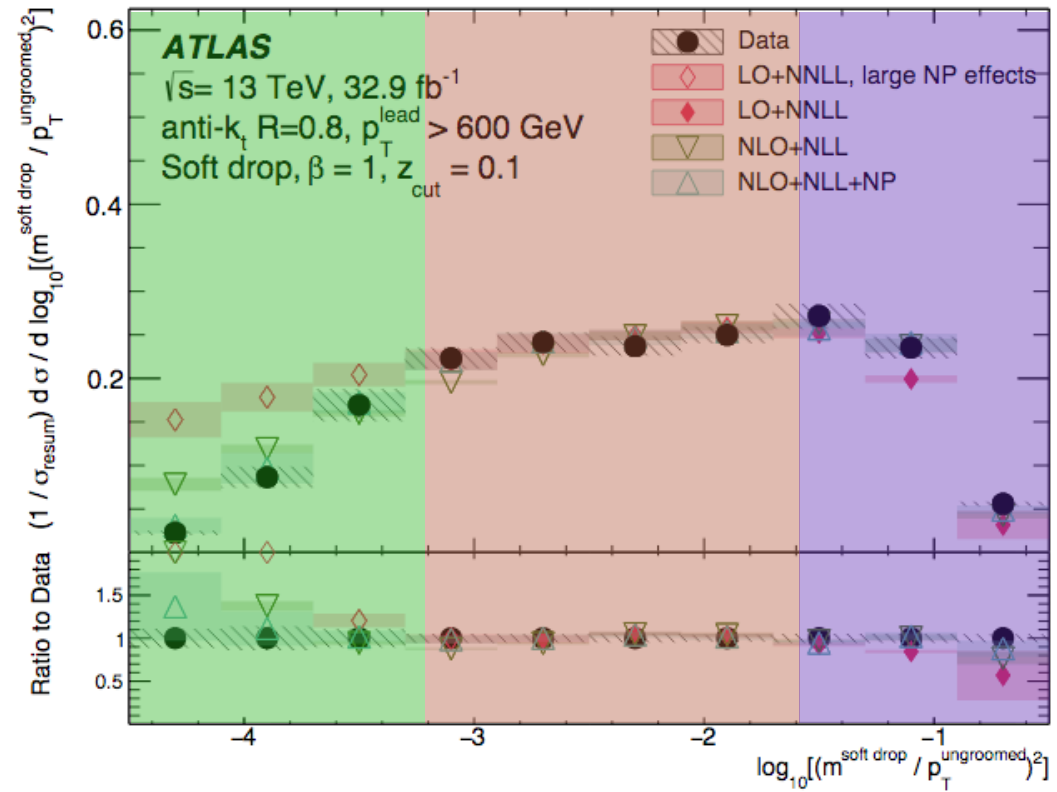
•Charged + Neutral



Comparison to Data

- Soft Drop jet mass NLO + NLL +NP
- Agree with data even in non-perturbative regime

Phys.Rev.Lett. 121 (2018)



$$\rho = 2 \log_{10}(m^{\text{SoftDrop}} / p_T^{\text{Ungroomed}})$$



27

$$\frac{d\sigma}{dm^2} = \sum_{k=q,g} D_k S_{C,k} \otimes J_k + \frac{d\sigma_{\text{fin.}}}{dm^2}$$

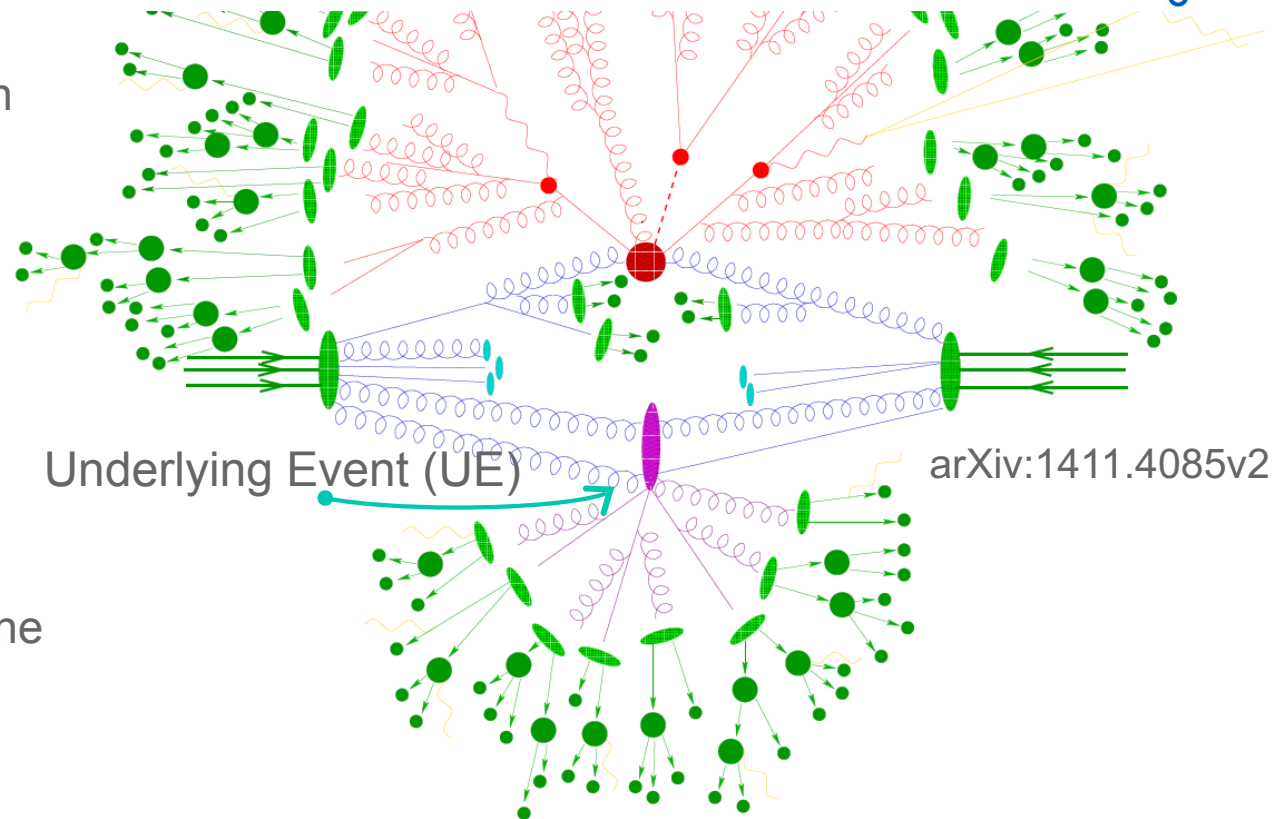
Collinear-Soft function
 Jet function
 Finite Matching Correction
 Cross section of quark or gluon jet produced

- [arXiv:1603.06375](https://arxiv.org/abs/1603.06375)



Generating Jets

- Hadron-hadron collision simulated by an MC event generator
 - Red dots: Hard scatter
 - Light green blobs: Parton-to-hadron transitions
 - Dark green blobs: hadron decays
- All decay products of one or more hard scatters can be clustered into a single jet
- Experimentally measured jet energies should correspond to energy of hard parton from the calculation *



NNLO PDFs

$$\begin{aligned}
 \sigma^{pp \rightarrow X + \dots} &= \sum_{ij} \int_0^1 dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \\
 &\times \hat{\sigma}_{ij \rightarrow X + \dots} \left(x_1, x_2, \{p_i^\mu\}, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2} \right)
 \end{aligned}$$

Calculated from Hard scatter matrix element

* Assuming that your jet clustering algorithm is collinear and infrared safe, like Anti-Kt which is used in this analysis.